Effects of Residue Background Events in Direct Detection Experiments on Determining Properties of Halo Dark Matter

Chung-Lin Shan

Department of Physics, National Cheng Kung University

IDM 2010, Montpellier, France

July 27, 2010

based on arXiv:1003.5277 [hep-ph], JCAP 1006, 029

Model-independent data analyses
- Motivation
- Reconstruction of the WIMP velocity distribution
- Determination of the WIMP mass

Effects of residue background events
- Measured recoil spectrum
- On the determination of the WIMP mass
- On the reconstruction of the WIMP velocity distribution

Summary

Model-independent data analyses

Motivation

- Differential event rate for elastic WIMP-nucleus scattering

$$\frac{dR}{dQ} = \mathcal{A} F^2(Q) \int_{v_{\rm min}}^{v_{\rm max}} \left[\frac{f_1(v)}{v}\right] dv$$

Here

$$v_{\rm min} = \alpha \sqrt{Q}$$

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy Q in the detector.

$$\mathcal{A} \equiv \frac{\rho_0 \sigma_0}{2 m_\chi m_{\rm r,N}^2} \qquad \alpha \equiv \sqrt{\frac{m_{\rm N}}{2 m_{\rm r,N}^2}} \qquad m_{\rm r,N} = \frac{m_\chi m_{\rm N}}{m_\chi + m_{\rm N}}$$

ρ_0: WIMP density near the Earth

σ_0: total cross section ignoring the form factor suppression

$F(Q)$: elastic nuclear form factor

$f_1(v)$: one-dimensional velocity distribution of halo WIMPs

Motivation

- Differential event rate for elastic WIMP-nucleus scattering

$$\frac{dR}{dQ} = \mathcal{A} F^2(Q) \int_{v_{\rm min}}^{v_{\rm max}} \left[\frac{f_1(v)}{v} \right] dv$$

Here

$$v_{\rm min} = \alpha \sqrt{Q}$$

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy Q in the detector.

$$\mathcal{A} \equiv \frac{\rho_0 \sigma_0}{2 m_\chi m_{\rm r,N}^2} \qquad \alpha \equiv \sqrt{\frac{m_{\rm N}}{2 m_{\rm r,N}^2}} \qquad m_{\rm r,N} = \frac{m_\chi m_{\rm N}}{m_\chi + m_{\rm N}}$$

ρ_0: WIMP density near the Earth

σ_0: total cross section ignoring the form factor suppression

$F(Q)$: elastic nuclear form factor

$f_1(v)$: one-dimensional velocity distribution of halo WIMPs

成功大學

Reconstruction of the WIMP velocity distribution

- Ansatz: reconstructing the measured recoil spectrum in the nth Q-bin

$$\left(\frac{dR}{dQ}\right)_{\mathrm{expt},\ Q\simeq Q_n} \equiv r_n\, e^{k_n(Q-Q_{s,n})} \qquad r_n \equiv \frac{N_n}{b_n}$$

- Logarithmic slope and shifted point in the nth Q-bin

$$\overline{Q-Q_n}|_n \equiv \frac{1}{N_n}\sum_{i=1}^{N_n}(Q_{n,i}-Q_n) = \left(\frac{b_n}{2}\right)\coth\left(\frac{k_n b_n}{2}\right) - \frac{1}{k_n}$$

$$Q_{s,n} = Q_n + \frac{1}{k_n}\ln\left[\frac{\sinh(k_n b_n/2)}{k_n b_n/2}\right]$$

- Reconstructing the one-dimensional WIMP velocity distribution

$$f_1(v_{s,n}) = \mathcal{N}\left[\frac{2Q_{s,n}r_n}{F^2(Q_{s,n})}\right]\left[\frac{d}{dQ}\ln F^2(Q)\bigg|_{Q=Q_{s,n}} - k_n\right]$$

$$\mathcal{N} = \frac{2}{\alpha}\left[\sum_a \frac{1}{\sqrt{Q_a}\,F^2(Q_a)}\right]^{-1} \qquad v_{s,n} = \alpha\sqrt{Q_{s,n}}$$

[M. Drees and CLS, JCAP 0706, 011]

Determination of the WIMP mass

- Estimating the moments of the WIMP velocity distribution

$$\langle v^n \rangle = \alpha^n \left[\frac{2Q_{\rm min}^{1/2} r_{\rm min}}{F^2(Q_{\rm min})} + I_0 \right]^{-1} \left[\frac{2Q_{\rm min}^{(n+1)/2} r_{\rm min}}{F^2(Q_{\rm min})} + (n+1) I_n \right]$$

$$I_n = \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)} \qquad r_{\rm min} = \left(\frac{dR}{dQ} \right)_{{\rm expt},\, Q=Q_{\rm min}} = r_1\, e^{k_1 (Q_{\rm min} - Q_{s,1})}$$

[M. Drees and CLS, JCAP 0706, 011]

Determination of the WIMP mass

- Estimating the moments of the WIMP velocity distribution

$$\langle v^n \rangle = \alpha^n \left[\frac{2Q_{\rm min}^{1/2} r_{\rm min}}{F^2(Q_{\rm min})} + I_0 \right]^{-1} \left[\frac{2Q_{\rm min}^{(n+1)/2} r_{\rm min}}{F^2(Q_{\rm min})} + (n+1) I_n \right]$$

$$I_n = \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)} \qquad r_{\rm min} = \left(\frac{dR}{dQ} \right)_{{\rm expt},\ Q=Q_{\rm min}} = r_1\, e^{k_1 (Q_{\rm min} - Q_{s,1})}$$

[M. Drees and CLS, JCAP 0706, 011]

- Determining the WIMP mass

$$m_\chi \big|_{\langle v^n \rangle} = \frac{\sqrt{m_X m_Y} - m_X \mathcal{R}_n}{\mathcal{R}_n - \sqrt{m_X / m_Y}}$$

$$\mathcal{R}_n = \left[\frac{2Q_{{\rm min},X}^{(n+1)/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + (n+1) I_{n,X}}{2Q_{{\rm min},X}^{1/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + I_{0,X}} \right]^{1/n} \Big(X \longrightarrow Y \Big)^{-1} \qquad (n \neq 0)$$

[CLS and M. Drees, arXiv:0710.4296]

- With the assumption of a dominant SI WIMP-nucleus interaction

$$m_\chi \big|_\sigma = \frac{(m_X / m_Y)^{5/2}\, m_Y - m_X \mathcal{R}_\sigma}{\mathcal{R}_\sigma - (m_X / m_Y)^{5/2}} \qquad \mathcal{R}_\sigma = \frac{\mathcal{E}_Y}{\mathcal{E}_X} \left[\frac{2Q_{{\rm min},X}^{1/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + I_{0,X}}{2Q_{{\rm min},Y}^{1/2} r_{{\rm min},X} / F_Y^2(Q_{{\rm min},Y}) + I_{0,Y}} \right]$$

[M. Drees and CLS, JCAP 0806, 012]

Effects of residue background events

Measured recoil spectrum

- Background spectrum
  - Target-dependent exponential background spectrum

$$\left(\frac{dR}{dQ}\right)_{\rm bg,ex} = \exp\left(-\frac{Q/{\rm keV}}{A^{0.6}}\right)$$

  - Constant background spectrum

Measured recoil spectrum

- Background spectrum
  - Target-dependent exponential background spectrum

$$\left(\frac{dR}{dQ}\right)_{\rm bg,ex} = \exp\left(-\frac{Q/{\rm keV}}{A^{0.6}}\right)$$

  - Constant background spectrum

- Background window
  - Entire experimental possible energy range (0 – 100 keV)
  - Low energy range (0 – 50 keV)
  - High energy range (50 – 100 keV)

Measured recoil spectrum

- Background spectrum
  - Target-dependent exponential background spectrum

$$\left(\frac{dR}{dQ}\right)_{\rm bg,ex} = \exp\left(-\frac{Q/{\rm keV}}{A^{0.6}}\right)$$

  - Constant background spectrum

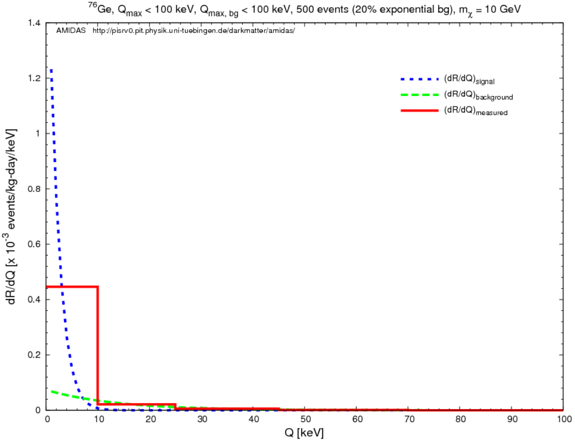
- Background window
  - Entire experimental possible energy range (0 – 100 keV)
  - Low energy range (0 – 50 keV)
  - High energy range (50 – 100 keV)

- (Naively) simulate
  - only a few residue background events
  - induced by two or more different sources

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, $m_\chi = 10$ GeV)

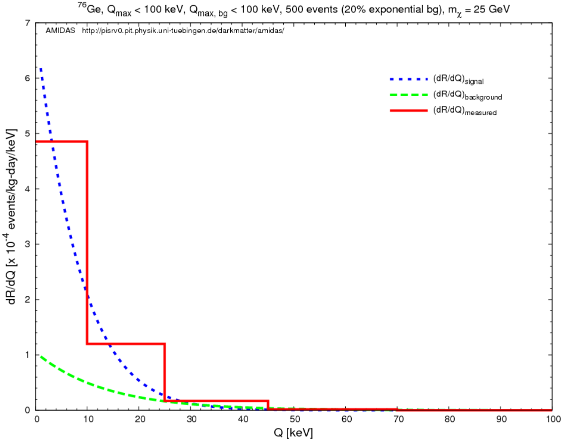


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, $m_\chi = 25$ GeV)

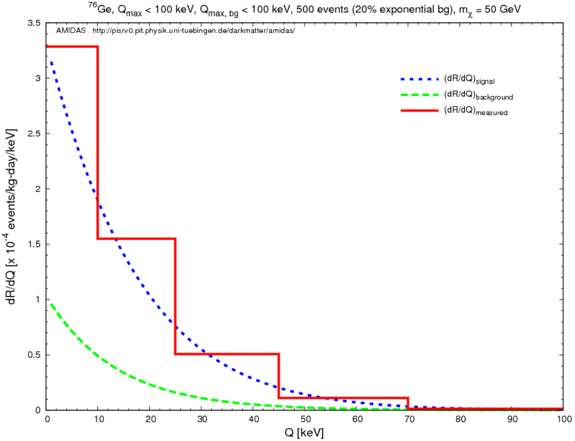


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, $m_\chi = 50$ GeV)

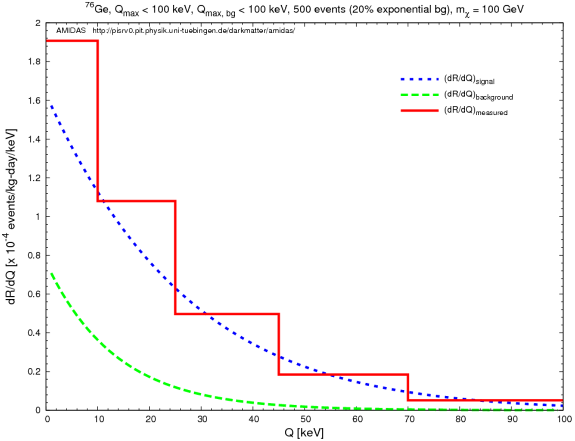


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, m_χ = 100 GeV)

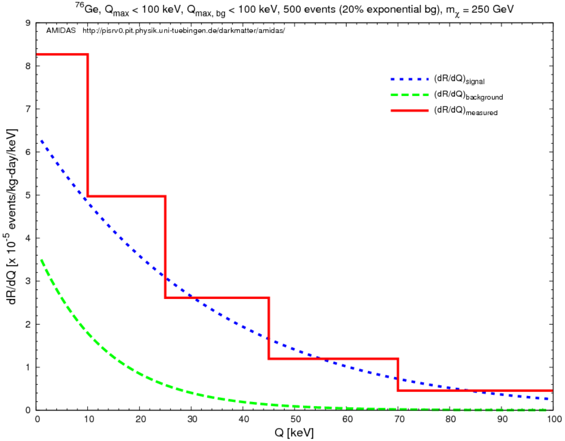


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, $m_\chi = 250$ GeV)

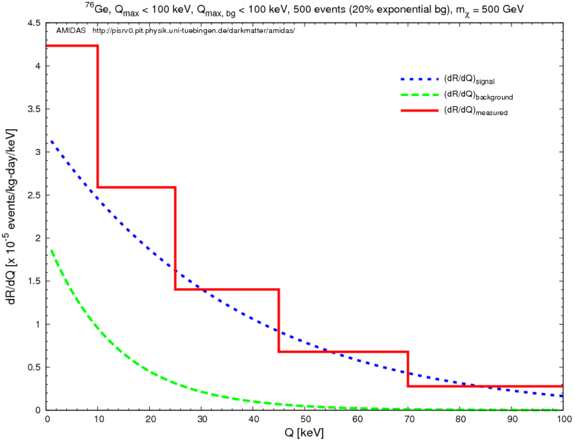


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

Measured recoil spectrum

- Measured recoil spectrum

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, 20% bg, m_χ = 500 GeV)



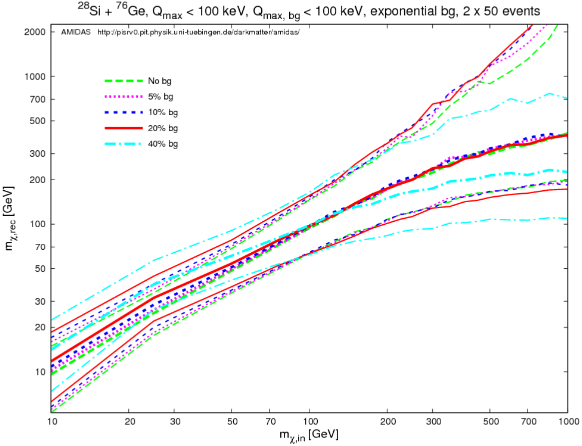
[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

On the determination of the WIMP mass

On the determination of the WIMP mass

- Reconstructed $m_{\chi,\mathrm{rec}}$

(^{28}Si + ^{76}Ge, 0 − 100 keV, exponential bg 0 − 100 keV, 2 × 50 events)

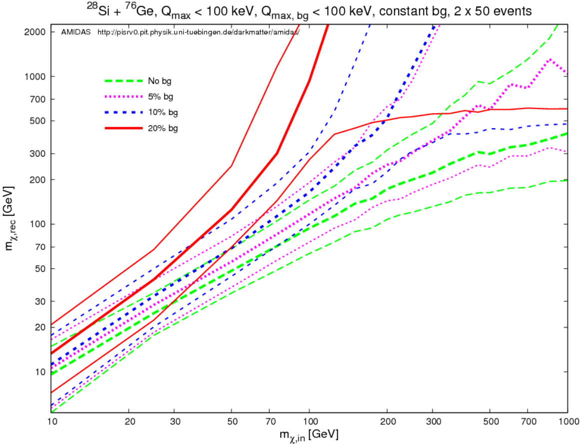


[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

On the determination of the WIMP mass

- Reconstructed $m_{\chi,\mathrm{rec}}$

  (^{28}Si + ^{76}Ge, 0 − 100 keV, constant bg 0 − 100 keV, 2 × 50 events)



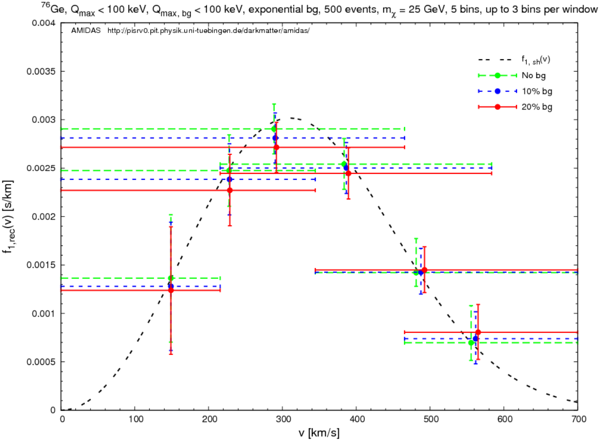
[Y. T. Chou and CLS, arXiv:1003.5277, accepted by JCAP]

On the reconstruction of the WIMP velocity distribution

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\mathrm{rec}}(v_{s,n})$

  (^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, $m_\chi = 25$ GeV)

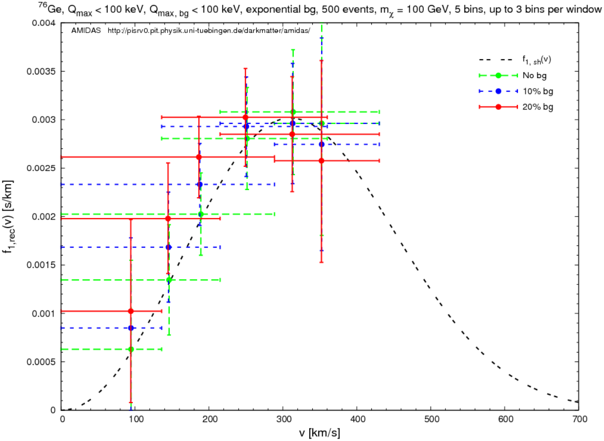


[CLS, JCAP 1006, 029]

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\rm rec}(v_{s,n})$

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, $m_\chi = 100$ GeV)

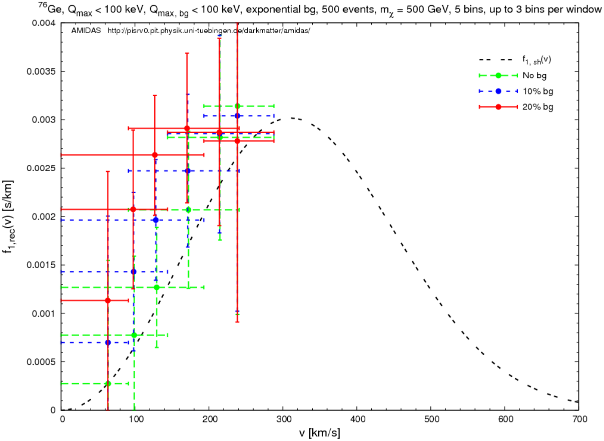


[CLS, JCAP 1006, 029]

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\mathrm{rec}}(v_{s,n})$

(^{76}Ge, 0 – 100 keV, exponential bg 0 – 100 keV, 500 events, $m_\chi = 500$ GeV)



[CLS, JCAP 1006, 029]

On the reconstruction of the WIMP velocity distribution

- Kinematic maximal cut-off of the recoil energy

$$Q_{\rm max,kin} = \frac{v_{\rm esc}^2}{\alpha^2}$$

- Reconstruction of the one-dimensional WIMP velocity distribution

$$f_1(v_{s,n}) = \mathcal{N} \left[\frac{2 Q_{s,n} r_n}{F^2(Q_{s,n})} \right] \left[\frac{d}{dQ} \ln F^2(Q) \bigg|_{Q=Q_{s,n}} - k_n \right]$$

$$\mathcal{N} = \frac{2}{\alpha} \left[\sum_a \frac{1}{\sqrt{Q_a}\, F^2(Q_a)} \right]^{-1}$$

$$v_{s,n} = \alpha \sqrt{Q_{s,n}}$$

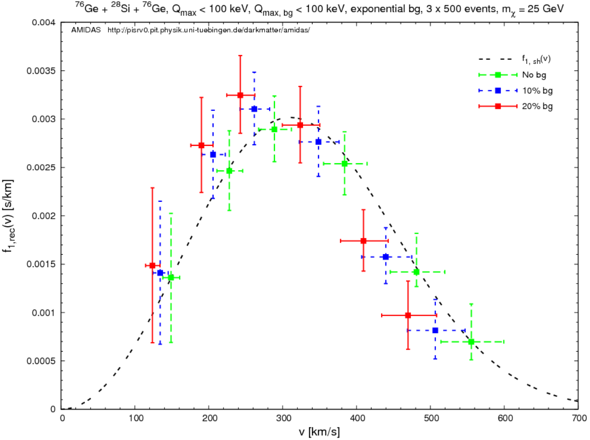
$$\alpha \equiv \sqrt{\frac{m_{\rm N}}{2 m_{\rm r,N}^2}} = \frac{1}{\sqrt{2 m_{\rm N}}} \left(1 + \frac{m_{\rm N}}{m_\chi} \right)$$

[M. Drees and CLS, JCAP 0706, 011]

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\mathrm{rec}}(v_{s,n})$ with reconstructed $m_{\chi,\mathrm{rec}}$

(^{76}Ge + ^{28}Si + ^{76}Ge, 0 – 100 keV, exponential bg, 3 × 500 events, $m_\chi = 25$ GeV)

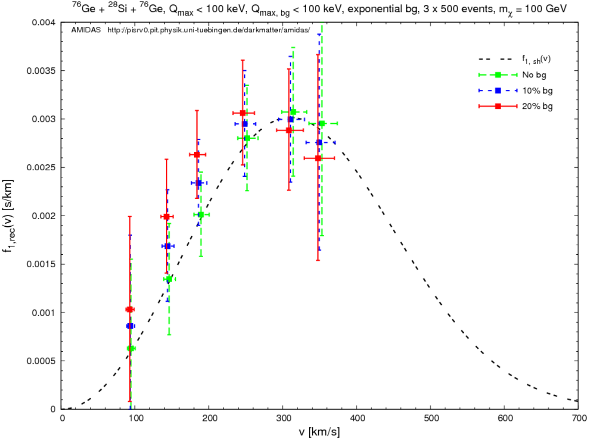


[CLS, JCAP 1006, 029]

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\text{rec}}(v_{s,n})$ with reconstructed $m_{\chi,\text{rec}}$

(^{76}Ge + ^{28}Si + ^{76}Ge, 0 – 100 keV, exponential bg, 3 × 500 events, m_χ = 100 GeV)

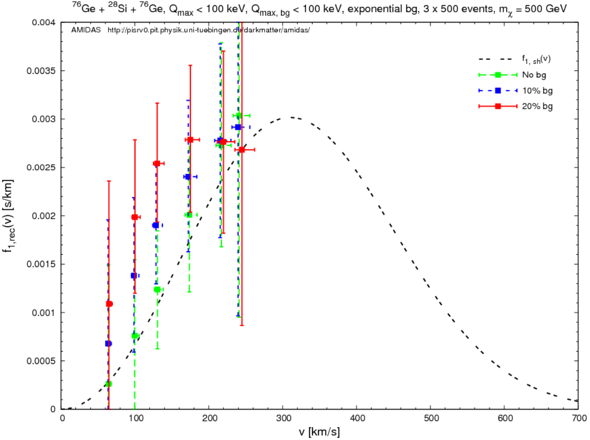


[CLS, JCAP 1006, 029]

On the reconstruction of the WIMP velocity distribution

- Reconstructed $f_{1,\text{rec}}(v_{s,n})$ with reconstructed $m_{\chi,\text{rec}}$

(^{76}Ge + ^{28}Si + ^{76}Ge, 0 − 100 keV, exponential bg, 3 × 500 events, m_χ = 500 GeV)



[CLS, JCAP 1006, 029]

Summary

Summary

- For determining m_χ
  - ➤ Background contribution in high/low energy ranges would over-/underestimate the reconstructed WIMP mass, especially if WIMPs are lighter/heavier than $\sim$ 50/200 GeV.
  - ➤ Maximal acceptable background ratio is $\sim 10\% - 20\%$.

Summary

- For determining m_χ
  - Background contribution in high/low energy ranges would over-/underestimate the reconstructed WIMP mass, especially if WIMPs are lighter/heavier than $\sim 50/200$ GeV.
  - Maximal acceptable background ratio is $\sim 10\% - 20\%$.
- For reconstructing $f_1(v)$
  - Background contribution in high/low energy ranges would shift the reconstructed WIMP velocity distribution to higher/lower velocities.
  - Over-/underestimated WIMP mass would (more strongly) shift the reconstructed WIMP velocity distribution to lower/higher velocities.
  - Maximal acceptable background ratio is $\sim 5\% - 10\%$.

Summary

- For determining m_χ
  - Background contribution in high/low energy ranges would over-/underestimate the reconstructed WIMP mass, especially if WIMPs are lighter/heavier than $\sim$ 50/200 GeV.
  - Maximal acceptable background ratio is $\sim$ 10% – 20%.
- For reconstructing $f_1(v)$
  - Background contribution in high/low energy ranges would shift the reconstructed WIMP velocity distribution to higher/lower velocities.
  - Over-/underestimated WIMP mass would (more strongly) shift the reconstructed WIMP velocity distribution to lower/higher velocities.
  - Maximal acceptable background ratio is $\sim$ 5% – 10%.
- For estimating $|f_\text{p}|^2$

Preliminary results will be given at SUSY10!

Summary

Thank you very much for your attention

[http://myweb.ncku.edu.tw/∼clshan/Publications/Talks/]